Crustal Movement Observed at Amagase Observatory

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Abstract

The secular variations of ground-strains and -tilts since 1967 obtained from observation carried out by extensometers, tiltmeters and electro-optical distance measurement have been described. The averaged annual rate of strains and tilts are the contraction of order of 10^{-6}/year for the results from extensometers and electro-optical distance measurements and 1''/year for the horizontal pendulum tiltmeters, respectively. For the water-tube tiltmeter the tilt is one order smaller than that of the horizontal pendulum tiltmeter. The trend of secular variations has changed slightly after 1976. The annual variations of the order of 10^{-6} for the strains derived from extensometers normal to the tunnel axis appear associated with rainfall.

1. Introduction

The Amagase Observatory is located in the central part of the Kinki district, Japan. Its geographic coordinates are 34°52'48'' N, 135°50'09'' E and 60 m above mean sea level. The observational site, established in the disused tunnel of a hydraulic power station, is located at 400 m from the entrance of the tunnel and at the depth of 140 m. Its geological constituent is identified as a black slate belonging to paleozoic formations. The velocities of P and S waves, obtained from the data of quarry blasts, are 4.66 km/sec and 2.58 km/sec[1]. The continuous observation of ground-strain and ground-tilt have been carried out since 1967 by the super-invar-bar extensometers, the super-invar-wire extensometer, the tiltmeters of horizontal pendulum type and the water-tube tiltmeters. In addition to these observations, the electro-optical distance measurements by a AGA Geodimeter have also been carried out since 1970 for the comparison with ground-strain obtained from extensometers. In April 1977, the telemetry recording system was introduced and the observed data have been transmitted over a standard telephone circuit to the Disaster Prevention Research Institute about 5 km away.

In this paper the secular variations of ground-strains and -tilts for the period from June 1967 to 1982 are described.

2. Observation and Recording

The location map and the topographic profile of the Amagase Observatory

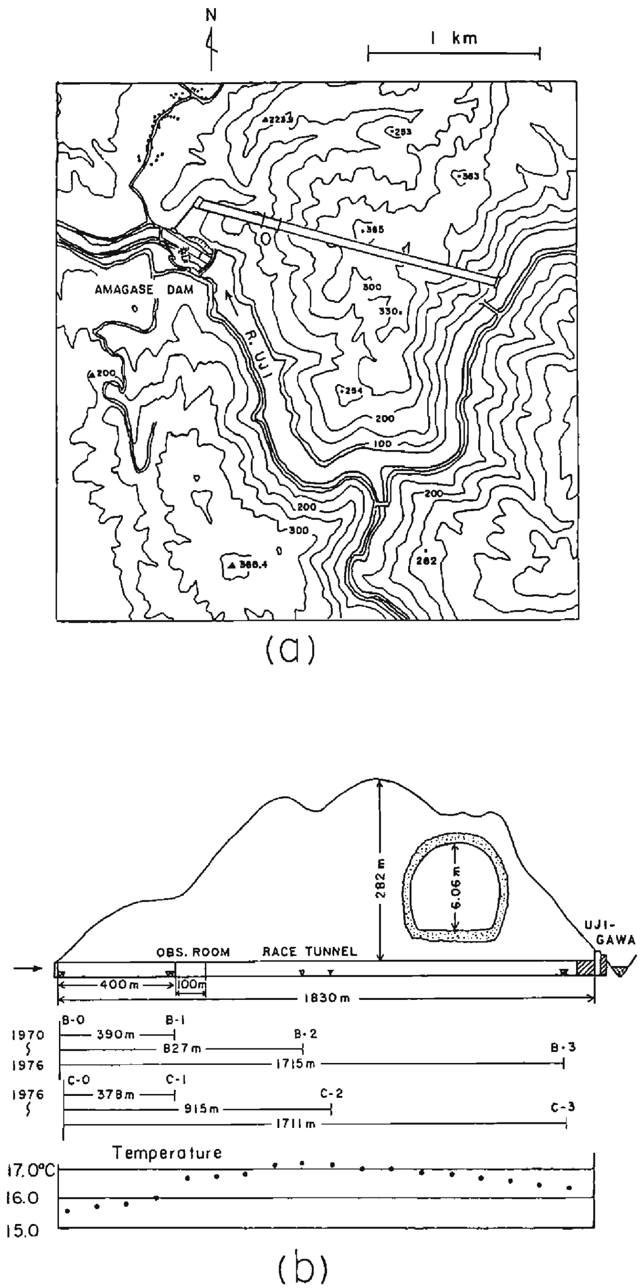

Fig. 1. Location map of the Amagase Observatory (a) and topographic profile along the observational tunnel and positions of the station mark for electro-optical distance measurements and temperature distribution along the tunnel (b).

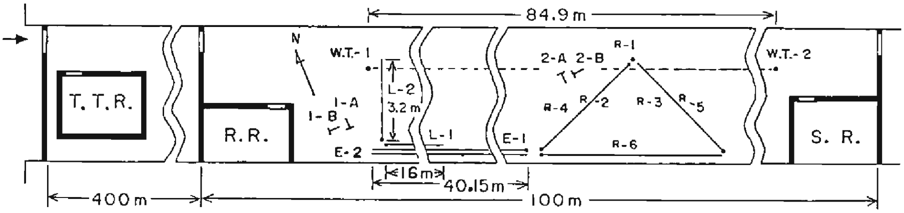

Fig. 2. Arrangement of instruments. E–1: Super-invar-bar extensometer (40 m span), E–2: Super-invar-wire extensometer, R–1–R–6: 6 component super-invar-bar extensometers, L–1,2: Laser extensometers, 1–A, B and 2–A,B: Tiltmeters of horizontal pendulum type, WT–1,2: Water-tube tiltmeter with 84.9 m base-line, S. R.: Seismometer room, R. R.: Recording room, T. T. R.: Telemetry transmitter room.

are shown in **Fig. 1**(**a**) and (**b**). The tunnel has the total length of 1830 m and is a straight line with a gradient of 1/1300. The southward side of the observational site is surrounded by the reservoir of Amagase dam. The section of the tunnel has a horseshoe shape with a diameter of about 6 m. Four station marks for electro-optical distance measurement are settled along the tunnel at the positions of B-0 to B-3 during 1970 to 1975 and replaced by those of C-0 to C-3 since 1976. The instruments are installed at a location between 400 m and 500 m from the entrance. The arrangement of instruments is illustrated in **Fig. 2**. E-1 shows the super-invar-bar extensometer of 40 m span with roller type magnification. E-2 is the super-invar-wire extensometer with the same length as E-1. R-1 to R-6 are six components of super-invar-bar extensometers which consist of three horizontal, one vertical and two oblique components. L-1 and L-2 indicate the laser extensometers. 1-A, 1-B, 2-A and 2-B indicate the horizontal pendulum tiltmeters and WT-1 and WT-2 the water-tube tiltmeter with base length of 84.9 m. S.R. is the seismometer room where a 3 component set of short-period seismometers with a natural period of 1.0 sec and a 3 component set of long-period seismometers with a free period of 20 sec are installed[2)].

Records of the roller and wire type super-invar extensometers and of the tiltmeters have been obtained on photographic paper by optical method. Since 1978, in addition to these records, the direct digital recording system with a photo-electric converter has also been used. This system was designed to reproduce records as digital quantities from optical magnifying apparatus of the extensometer or tiltmeter[3)]. A photo-transistor, translated at a speed of 10 mm/sec on the drive shaft by a synchronous motor, receives the light beam from the lamp used for the reference line of measurement of strain or tilt and generates one pulse which operates as the opening signal of the counter gate. The photo-transistor receives the light beam from the mirror of magnifying apparatus of extensometer or tiltmeter successively and generates another pulse which operates as the closing signal of the gate. In this way the deflection of the light beam from the extensometer or tiltmeter is converted into the time interval between two pulses, which is measured by counting 100 Hz pulses by an IC counter. The output from this counter produces 11-bit binary digital data.

As for the water-tube tiltmeter, the water level had been directly measured with a micrometer since the beginning of observation in 1967. But the measurement was interrupted from 1973 to 1977 because of water leaking at joint of the pipe. In 1977 concrete piers were newly constructed, and the pipes were replaced by transparent acrylic pipes. At the same time the recording system was changed to an automated digital system using a float-type transducer and a photo-electric converter.

Laser extensometers have been operated with laser interferometer system. The details of this system have been described in another paper[4].

Table 1 List of observing instruments.

Observing Instrument	Mark	Azimuth	Span or Period	Sensitivity
Super-invar Bar Extensometer	E–1	N72.5°W Horizontal	40.24 m	6.09×10^{-9}/mm 0.51×10^{-9}/digit
Super-invar Bar Extensometer (6 Components)	R–1	Vertical	5.80 m	3.59×10^{-8}/mm 3.51×10^{-9}/digit
	R–2	N62.5°E Horizontal	5.54	3.84×10^{-8}/mm 3.76×10^{-9}/digit
	R–3	N27.5°W Horizontal	5.54	3.84×10^{-8}/mm 3.90×10^{-9}/digit
	R–4	N62.5°E Dip-55°S	8.10	2.51×10^{-8}/mm 2.71×10^{-9}/digit
	R–5	N27.5°W Dip-55°S	8.10	2.50×10^{-8}/mm 2.55×10^{-9}/digit
	R–6	N72.5°W Horizontal	8.15	2.79×10^{-8}/mm 2.80×10^{-9}/digit
Super-invar Wire Extensometer	E–2	N72.5°W Horizontal	40.24 m	2.41×10^{-9}/mm 0.60×10^{-9}/digit
Tiltmeter of Horizontal Pendulum Type	PT1–A	W Down	29.7 sec.	1.18×10^{-2}″/mm 1.66×10^{-3}″/digit
	PT1–B	N Down	29.6	1.18×10^{-2}″/mm 1.69×10^{-3}″/digit
	PT2–A	E Down	29.8	1.25×10^{-2}″/mm
	PT2–B	N Down	29.7	1.28×10^{-2}″/mm
Water Tube Tiltmeter	WT	N72.5°W	84.9 m	0.05 μm/digit
Laser Extensometer	L–1	N72.5°W	16.0 m	1.0×10^{-9}/digit
	L–2	N17.5°E	3.2	5.0×10^{-9}/digit
Short Period Seismograph		Z	1.0 sec.	1.9 μkine/digit
		NS	1.0	1.9
		EW	1.0	1.9
Long Period Seismograph		Z	20.0 sec.	0.3 μm/digit(20sec.)
		NS	20.0	0.3
		EW	20.0	0.3

The outputs from these instruments are transmitted over a standard telephone circuit to the our laboratory about 5 km away by the FATEC 130 telemetry recording system. Operations of the photo-electric converter are controlled by address signals transmitted every two minutes from a mini-computer PFU-100 set up at our laboratory. The transmitted data are successively stored into a mini-computer. The stored data are punched out on paper tape and printed out by a tele-printer at midnight and noon every day.

Table 1 shows the list of observation instruments and the sensitivity of each instrument.

3. Data Processing

The data recorded on paper tape by the telemetry system are transferred to magnetic tape and disk pack and edited on the computer for convenience of data processing. At that time the lacking data due to troubles of the telemeter system are complemented manually by card input data. The magnetic tape is used for the data library which contains multi-files of each daily recording. On the disk pack annual data are filed according to year and used for analytical procedures.

At the first stage of the data processing, interruptions of record, unusual values and discontinuities of average line are corrected. The short time interruptions or unusual data are automatically detected by the comparison of difference in two successive data with permitted limits given for every component, and interpolated by a linear line connecting both data just prior to and following an abnormal interval. Long time interruptions are manually connected using a linear interpolation method or replaced by the data from monitoring photographic records. Discontinuities on averaged lines are removed using correction values obtained from comparison of the linear trends determined by the least-squares method for 72 hours before and after the discontinuity. And then these corrected data are normalized by the instrumental sensitivities. The interval of the corrected data and the values before and after correction are printed out.

As the second stage of data processing, the long-period components beyond 24 hours and the short-period components which mainly consist of a tidal constituent are separated by the 25 hours moving average. These data are plotted on an X-Y plotter in the order of the raw data, the long-period component and the short-period one. For the smoothed data, the data of every 12 hours are stored on another file and used for analysis of long term secular variations. The main part of the analysis in this paper has been carried out using these data of this file. For the ground-tilt the vector diagrams are also plotted. Such data processing has been made every month and the amount of monthly variations and the appearance of unusual variation have been examined.

For data before 1977 the reading value of photographic records at 00 hours every day are used for data analysis.

4. Long Term Variations of Strain and Tilt

Variations of ground-strains and ground-tilts and the precipitation since 1967 are illustrated in **Fig. 3**. Records of strains and tilts are the daily values. Amounts of precipitation are the values accumulated for 10 days. At the beginning of observation significant variations appeared for all components. This was probably due to the effects of instrumental drift and contraction of concrete piers. These

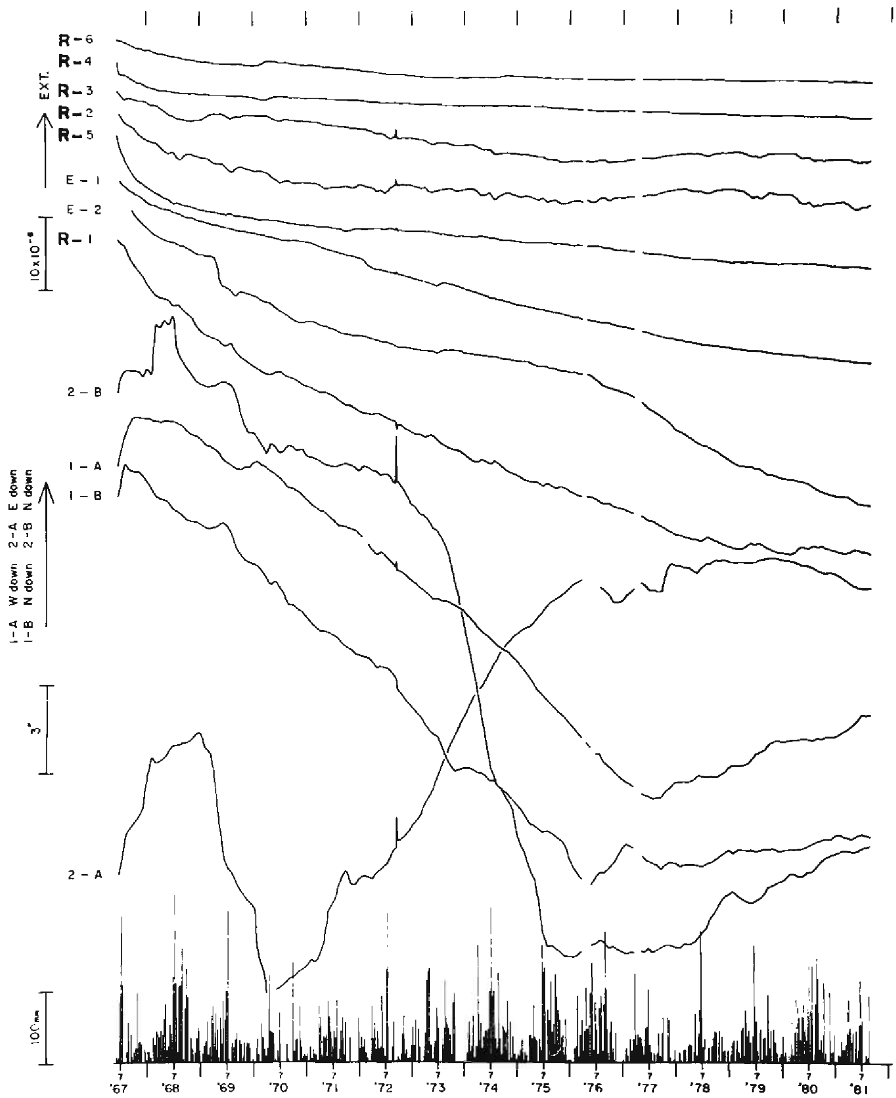

Fig. 3. Secular variations of ground-strains and -tilts and the 10 days precipitation observed at Amagase.

effects seemed to decrease almost exponentially with time. To examine definitely the long term variations of strains and tilts, the short period variations primarily caused by meteorological effects are eliminated by means of 13 months moving

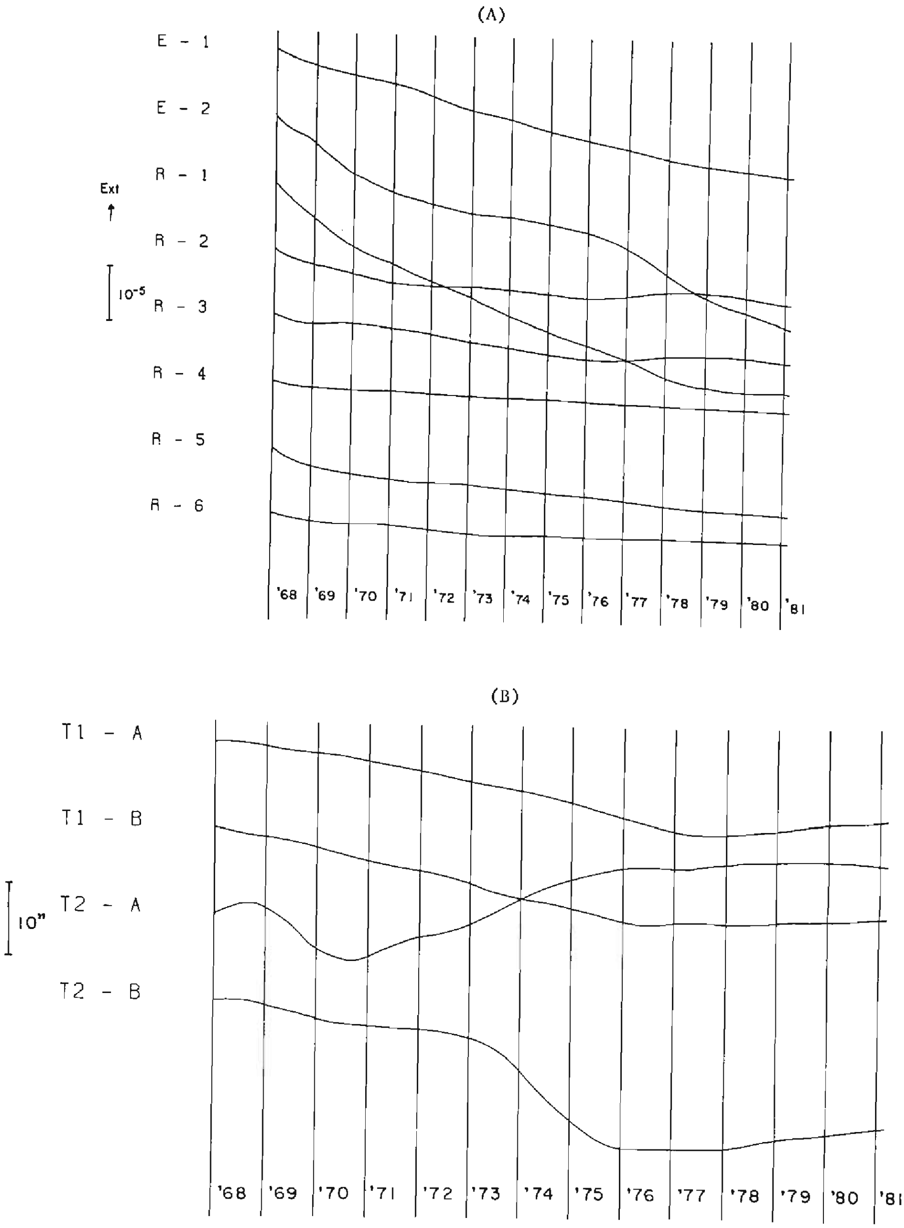

Fig. 4. Averaged secular variations of ground-strain and -tilt so that the short period components below one year are eliminated by 13 months moving average. (a): strains and (b): tilts.

average. Such averaged secular variations are shown in **Fig. 4(a)** and **(b)**.

For the period from 1970 to 1975 the trend of secular variations is uniform and linear for all components but has slightly changed after 1976. This change of trend is clearly recognized for tilts as seen in **Fig. 4(b)**. The trend of strain variations is generally contraction except for the two horizontal components in the direction of 45° across the tunnel, R-2 and R-3, which have the trend of extention for the period from 1976 to early 1979. For E-1 and R-6, oriented parallel to the tunnel axis, and R-4 and R-5, inclined to the vertical at an oblique angle of 55°, the change of trend in 1976 is not significant. For the wire type extensometer, E-2, installed in the same co-axial direction as E-1, the rate of contraction becomes large from 1976 to 1978. However, since the reliability of the wire type extensometer to long term variation may be inferior to the roller-type due to the instrumental constitution, that variation may not be considered to be significant with respect to quantity. The vertical component, R-1, shows significant change of the trend of variation in 1978. Consequently, it is considered that the trend change of strains in 1976 occurred significantly in the direction perpendicular to the tunnel axis. Another characteristic of strain variations is that the amount of the variation rate has become very small for all components since 1978 when the telemetry recording system began to be operated. The average rate of secular strains are the contraction of order of 10^{-6}/year.

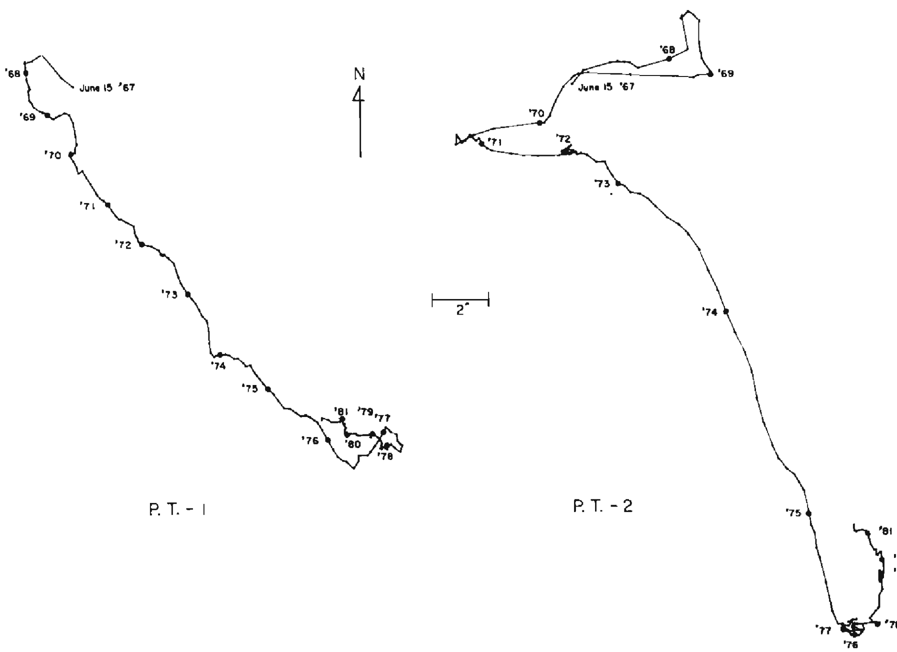

Fig. 5. Vector diagrams of ground-tilts. Upward vectors indicate tilt down to N and the right vectors tilt down to E.

The tilts observed by the horizontal pendulum tiltmeters indicate a uniform downward trend with the rate of about 2''/year in the SE direction from 1970 to 1976. Such trends agree qualitatively with the values recorded between PT-1 and PT-2 which have been installed about 45 m apart, but the amount of variations differs slightly between them. Since 1976 the direction of tilt has inverted downwards to the west for PT-1 or down to the north for PT-2 and the amount of variation rate has become very small. These tendencies are clearly found by the vector diagram of tilts illustrated in **Fig. 5**. In **Fig. 3** and **Fig. 4(b)** A and B indicate the E-W and N-S components, respectively, and the upward dircetion in the figures indicates down to the W for 1-A, down to the E for 2-A and down to the N for both 1-B and 2-B, respectively.

The tilts obtained from the water-tube tiltmeter are shown in **Fig. 6**. WT-1 and WT-2 indicate the records of water level at both ends of the same water-tube. Then WT-1 and WT-2 must vary in the opposite direction with each other to the ground-tilts. However, as seen in **Fig. 6**, their drifts tend to the same direction. These drifts may be probably caused by the decrease of water level due to spontaneous evaporation. WT means difference between WT-1 and WT-2. It may be

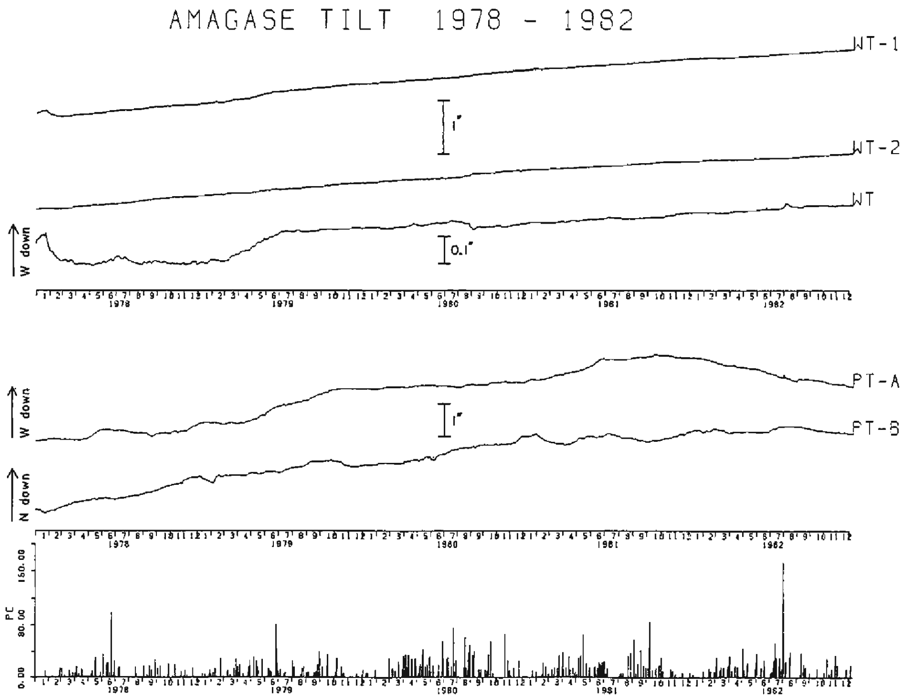

Fig. 6. Tilts observed with telemetry system for the period of 1978 to 1982. WT–1 and WT–2 are records observed at the two end points of the same water-tube. WT is the difference between WT–1 and WT–2. PT–A and PT–B are E–W and N–S components of horizontal pendulum type tiltmeters, respectively.

Table 2. Averaged annual rate of strains and tilts at Amagase for the periods from 1967 to 1981 and from 1978 to 1982.

	1967–1981	1978–1982
Strains	$\times 10^{-6}$/year	$\times 10^{-6}$/year
E-1	-1.670 ± 0.016	-0.955 ± 0.0003
E-2	-2.516 ± 0.038	-1.600 ± 0.0015
R-1	-2.738 ± 0.045	-0.426 ± 0.0028
R-2	-0.507 ± 0.026	-0.778 ± 0.0027
R-3	-0.570 ± 0.018	-0.769 ± 0.0020
R-4	-0.308 ± 0.006	-0.406 ± 0.0005
R-5	-0.746 ± 0.018	-0.650 ± 0.0006
R-6	-0.292 ± 0.010	-0.278 ± 0.0003
Dilatation	-3.815 ± 0.056	-1.973 ± 0.0025
Tilts	"/year	"/year
PT 1-A	-0.971 ± 0.028	0.492 ± 0.0028
PT 1-B	-1.012 ± 0.031	0.493 ± 0.0015
PT 2-A	-0.936 ± 0.050	
PT 2-B	-1.682 ± 0.064	
WT		0.045 ± 0.0002

considered to be true ground-tilt that is free from the variation of water level due to evaporation and atmospheric pressure. WT indicates the trend down to the W with the very small rate of 0.05"/year except for the beginning of 1978 and the period from March to June 1979 when the amount of variation reached 0.1". Secular variations observed by the horizontal pendulum tiltmeter PT-1 and the water-tube tiltmeter WT are qualitatively consistent with each other, but the tilt obtained from the former are larger by about one order than that from the latter (average rate of PT-1-A is 0.5"/year and that of WT is 0.05"/year).

The summary of the linear trend of secular variations from 1968 to 1981 determined by the least squares method are shown in **Table 2**. For the comparison the values after 1978 obtained from the records of telemetry system are shown in the right column of **Table 2**. Volume dilatation is derived from the summation of R-1, R-2 and R-3 perpendicularly intersecting each other.

5. Strains from Electro-optical Distance Measurement

The three base-lines shown in **Fig. 1(b)** for measurement of the distance using electro-optical method have been installed along the tunnel. Such base-lines are designed to compare the strain accumulation in the short range obtained from extensometers with the strain accumulation across an area of a few km wide. The measurements have been repeatedly made with a Geodimeter Model 6 since 1970.

The annual change of temperature in the observational tunnel is less than 0.1°C and the humidity is constant (above 90%). Moreover, the distribution of temperature along the tunnel is measurable. Consequently, the correction error due to the uncertainty in temperature profile which has significant influence on the accuracy of Geodimeter measurement, may be very small. Then the very high precision can be expected in this measurement.

Fig. 1(**b**) illustrates the position of station marks, the approximated distances of lines and the temperature distribution along the lines. Baselines in the period 1970–1976 consist of four marks indicated by B-0, B-1, B-2 and B-3. In 1976 station marks were converted into the concrete bases to lessen the setting error of both Geodimeter and reflector. These four marks are illustrated in **Fig. 1**(**b**) by C-0, C-1, C-2 and C-3. Since all line lengths differ between B-lines and C-lines, it is not possible to compare directly the measurement values of distances with each other. However, if the strain calculated by dividing the fluctuations from the initial length for each line by the line length is used, it may be possible to compare the values for B-lines with values for C-lines. The results derived from such a procedure are shown in **Fig. 7**. The lowest part in **Fig. 7** shows the strain obtained from the extensometer E-1 which is 40 m in length.

The scattering of data increases as the line length decreases. The trends of strain change are contraction for all lines and are consistent with that of the extensometer. As the result of repair of Geodimeter in 1980 the instrumental constant changes slightly. For this reason the measurement values are treated separately for the period before and after 1980. The annual rates of strain change before 1980, as determined by a least squares linear fit, are (-1.62 ± 0.20), (-1.49 ± 0.45) and (-2.58 ± 0.92) μstrain/year for each line of (3–0), (2–0) and (1–0), respectively.

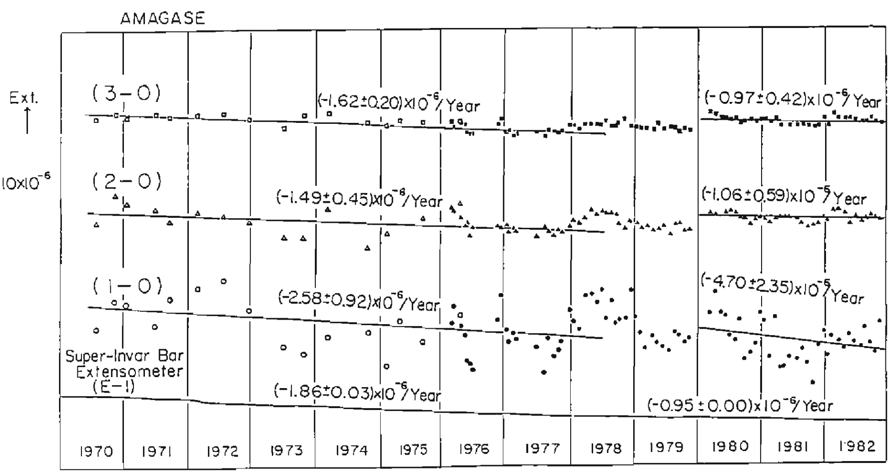

Fig. 7. Averaged strain rates obtained from electro-optical distance measurements and from the super-invar-bar extensometer (E–1) installed along the tunnel. The location and length of base lines (3–0), (2–0) and (1–0) are shown in Fig. 1 (b).

The annual rates from 1980 are (-0.97 ± 0.42), (-1.06 ± 0.59) and (-4.70 ± 2.35) μstrain/year, respectively. These rates for line (3–0) in which the deviation of the strain is smallest are consistent with the rates obtained from extensometer E-1 within the measurement uncertainties. Moreover, the annual rates of strains have generally become smaller since 1978 as mentioned above.

6. Short Term Variations of Strain and Tilt

It is required to consider the meteorological effect on strain and tilt in order to detect the rates of tectonic deformation that appear to be quite low. At Amagase Observatory the annual variation of strain and tilt due to the seasonal temperature variation is not significant. As for precipitation, the short period variation which correlates to individual rainfall is not found, but the response to the precipitation accumulated for a certain period is clearly noticed. This effect is most pronounced for R-1, R-2 and R-3 components of extensometers installed in the cross section normal to the axis of the tunnel. In **Fig. 8** ground-strains for 8 components of extensometers from 1978 to 1982 are illustrated. The trend of strain change due to precipitation is extension for the vertical direction and contraction for the horizontal

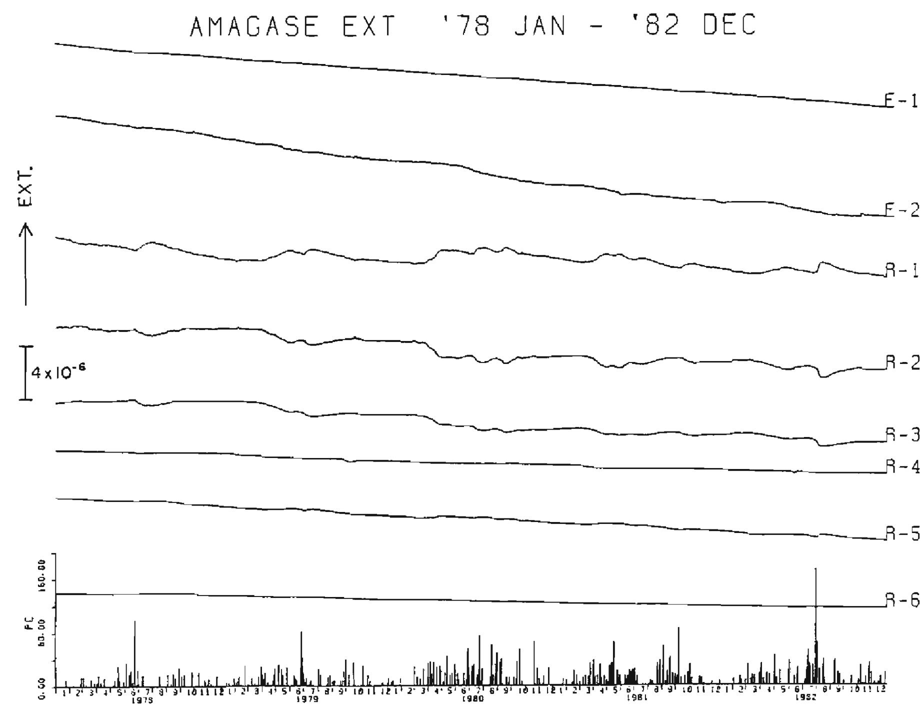

Fig. 8. Ground-strains for 8 components of super-invar-bar extensometers and daily precipitation from 1978 to 1982.

direction. For E-1, E-2 and R-6, installed along the tunnel, this effect is not significant. The volume dilatation derived as summation of three components perpendicular to each other indicates contraction. This suggests that the strain changes caused by rainfalls are dominated by the horizontal compressional stress normal to the tunnel. Since the period of strain change depends on the rainfall pattern, it may be impossible to estimate uniquely the most probable period of accumulation of precipitation to agree with the rainfall response of strain.

In the present case the strain components divided into some frequency bands through band-pass filters are compared with the precipitation accumulated for some time intervals chosen in correspondence to each bands. In **Fig. 9** the two bands of vertical component, R-1, and the precipitation during 90 days are shown. It is found that the low frequency component of strain with the long period above 180

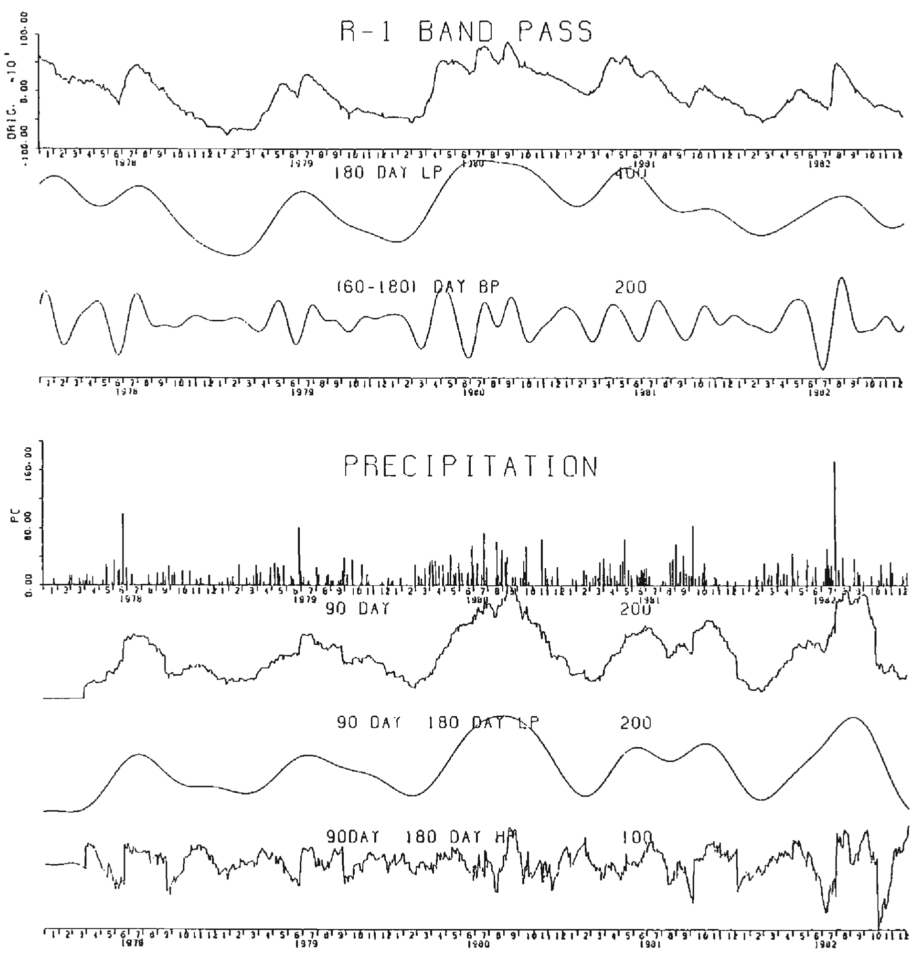

Fig. 9. Band-passed components of R–1 and 90 days precipitation.

days correlate remarkably with the precipitation during 90 days passed through 180 day low pass filter. The amount of strain with respect to the precipitation is about $2 \times 10^{-7}/100$ mm. For the shorter period ranges the correspondence between strain and precipitation also appear to be considerably good.

The rate of strain variation at the dry season is stationary and constant with respect to time. But the strain attributed to precipitation is not recovered at the dry season, and it seems that the residual strain accumulates with secular variation. This tendency was noted remarkably in 1980 when the annual precipitation was significantly greater than in the preceding two years. The amount of the residual strain between every dry season is in the order of about 1×10^{-6}.

The impulsive strain change independent of rainfall which, for example, appeared in October and December 1979 has good correspondence with the change of water-level of the reservoir associated with water discharge of the Amagase dam, which lies 500 m from the observational site. The amount of strain variation with respect to change in water level is about 2×10^{-8}/m, and the trend of variation is the same as the rainfall effect.

Characteristic tilt changes have not been observed at the time of rainfall and water discharge of the dam.

7. Conclusion

The secular variations of ground-strains and -tilts obtained from the observational system of the Amagase Crustal Movement Observatory since 1967 have been described. The averaged annual rate of strains is contraction of the order of 1 μstrain/year. For the roller type super-invar-bar extensometers this value of annual rate can be considered reliable according to the result examined with the laser interferometric calibration system[5]. This annual rate is also considered to be the case for the vicinity of Amagase observatory over the range of a few kilometers wide. This consideration comes from the result that the agreement between the strain rate derived from the extensometer and that from the electro-optical measurement is very good. The averaged annual rate of tilts of about 1 ''/year are derived from the horizontal pendulum tiltmeters, but that from the water-tube tiltmeter is one order smaller. The characteristic change of both the rate and the trend of secular variations in 1976 was common to all stations in the central part of Kinki district[6]. Any deformation would be aseismic since no earthquakes of any significance had occurred in the region adjacent to the site over the entire period. The annual variations of the order of 10^{-6} associated with rainfall appear for the ground-strains derived from extensometers normal to the tunnel axis. And also, the transient strain change of the order of 10^{-7} due to the fluctuation of the water level of the nearby reservoir have been observed in components normal the tunnel. These variations have been explained by the hydrological effect of groundwater pressures in the porous medium around the observational site[7]. Judging from the result that such large short-term strain changes are superposed to the averaged long-term strain, it may be considered to be dangerous to estimate the rate of the tectonic deformation and to detect the preseismic abnormal changes using the short period observational records.

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The data processing was run on a FACOM M-150 at the Information Data Processing Center for Disaster Prevention Research of the Disaster Prevention Research Institute of Kyoto University.

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